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Rift propagation across the Tibetan Plateau as a consequence of fluid flow from south to north

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ABSTRACT

The Tibetan Plateau is undergoing east-west extension manifested by north-trending rifts. Rift dynamics have been attributed to both mantle convection, which induces vertical motion causing general extension, and plate convergence, with northward motion causing along-strike extension, driven by the subducted Indian slab. However, the cause of lithospheric extension remains debated. We carried out electrical resistivity modeling of the entire Tibetan Plateau and present a quantitative interpretation of low-resistivity structures in terms of high fluid fraction and low viscosity. The model reveals low-resistivity features intruding and overlying the resistive lithosphere of Lhasa and Qiangtang. The low-resistivity features show a transition from vertically oriented to horizontally oriented positions at ∼50–70 km depth and appear to be oriented north-south below the Himalaya and Lhasa and east-west below Qiangtang. The anomalies can be explained by partial melts and fluids and may represent the signatures of material migration and locally weakened lithosphere. This material migration must have been significant enough to sustain rifting and drive the rift tips northward, despite the complex tectonic setting of the Tibetan Plateau, which is composed of a number of independent blocks. The results suggest that north-trending rifts were formed in response to fluid flow, after or during lithospheric foundering below Lhasa. Furthermore, fluid flow can explain the surface distribution of rifts in bands and the variations in rift formation and development between Qiangtang and Lhasa, which are attributed to the local rheological differences and specific regimes of vertical and/or horizontal stresses that are induced by fluid migration.

INTRODUCTION

The creation of the Tibetan Plateau resulted from the collision and convergence of the Indian continent into Eurasia since ca. 55 Ma (Di et al., 2023). Although the plateau has grown primarily through lithospheric contractional deformation and crustal thickening, active east-west extension is also a common mode of deformation (Yin et al., 1999). The mechanisms driving extension are not well understood, and several factors have been proposed, including convective removal of the mantle lithosphere, gravitational collapse of the crust, differences in the plate geometry or convergence rate along the collision zone, heterogeneities in the lower crust of the subducted plate, and progressive underthrusting of the Indian lithosphere (e.g., Flesch et al., 2001; Godin and Harris, 2014). Recent geophysical studies across Tibet have provided new insights and potential mechanisms causing extension, such as basal shear or slab tearing, based on seismic anisotropy (Zhang et al., 2023; Wu et al., 2019) and the viscous buckling model from viscosity simulations (Bischoff and Flesch, 2018). Moreover, previous rift studies were often spatially constrained to a few sections and limited geophysical results (Styron et al., 2015; Ozacar and Zandt, 2004; Unsworth et al., 2005; Jin et al., 2022; Zhang et al., 2023; for an exception, see Yang et al., 2020). In addition, they typically approximated the lithosphere as a homogeneous sheet (Flesch et al., 2001), neglecting extensional structures and their lateral and vertical heterogeneity. Understanding of the rifting in Tibet has been limited, in part, due to a lack of deep geophysical data and investigations into the material responses to extension, such as fluid migration.

The magnetotelluric (MT) method, which determines the subsurface electrical resistivity, is sensitive to in situ temperatures and fluid content and has been used to assess lithospheric strength, both globally (Türkoğlu et al., 2008; Di et al., 2023) and in Tibet (e.g., Unsworth et al., 2005; Wei et al., 2001; Jin et al., 2022). Knowledge of the large-scale electrical structure below Tibet is key to investigating fluid migration and its role in lithospheric extension. We generated a new three-dimensional (3-D) lithosphere-scale resistivity model that covers the Tibetan Plateau, revealing the heterogeneous distribution of conductive structures. The interpretation of these new findings attributes the north-trending rifting to fluid flow after or during lithospheric foundering below Lhasa, satisfying constraints from many independent geological observations of rifting during the India-Asia collision (e.g., Aoya et al., 2005; Bian et al., 2020).

RESULTS

MT measurements were acquired across the Tibetan Plateau, comprising an array of 375 measurements with a nominal spacing of 0.5° × 0.5° (Fig. 1), with a period range of 0.003–30,000 s (see SM1 and SM2 in the Supplemental Material[1]). The modeled area of interest was ∼1000 × 2000 km across and 200 km deep (SM3). The final electrical resistivity model (Fig. 2) was evaluated by comparing the model response to the measured data points using the standard approach of a normalized

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[1]Supplemental Material. Information regarding the magnetotelluric method and related parameter estimation methods. Please visit https://doi.org/10.1130/GEOL.S.28590788 to access the supplemental material; contact editing@geosociety.org with any questions.

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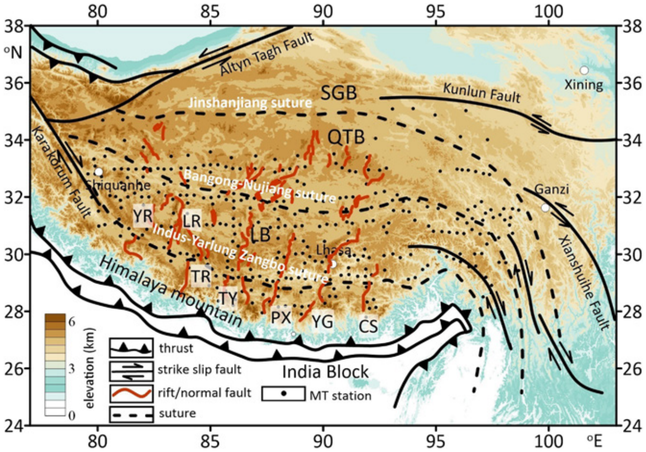

Figure 1. Tectonic map of Tibetan Plateau marked with rifts, normal faults, tectonic sutures, thrust faults, and magnetotelluric (MT) measurement locations. SGB—Songpan-Ganzi block; QTB—Qiangtang block; LB—Lhasa block; YR—Yare rift; TR—Thakkola rift; LR—Lunggar rift; TY—Tangra-Yumco rift; PX—Pumco-Xainza rift; YG—Yadong-Gulu rift; CS—Cona-Sangri rift (after Shi et al., 2020).

misfit criterion (SM3). Sensitivity tests were performed to assess the robustness of some model features (SM4).

The Jinshajiang (JSJS), Bangong-Nujiang (BNS), and Indus-Yarlung Zangbo (IYZS) sutures between the Songpan-Ganzi (SGB), Qiangtang (QTB), Lhasa (LB), and Tethys-Himalaya (THB) blocks, which mostly trend east-west, are revealed as conductive features (<10 Ω·m) in the upper crust (<25 km depths). The rifts and extensional structures exhibit conductive features (<10 Ω·m) in the upper crust, with a north-south orientation across the IYZS (perpendicular to the suture; Figs. 2A–2B), embedded in the generally resistive background (1000–10,000 Ω·m). At greater depths (Figs. 2C–2D), it appears that the Indian plate has subducted into the central Tibetan lithosphere, as indicated by the continuous high resistivity possibly extending 100 km north of the IYZS between 84°E and 94°E and north of the BNS on either side, a result that is consistent with previous studies, including Shi et al. (2020) and Jin et al. (2022).

The lower lithosphere below the Tethys-Himalaya and Lhasa terranes is characterized by a series of conductive (<20 Ω·m) and resistive features (>1000 Ω·m) roughly oriented north-south, whereas to the north, below Qiangtang, the lower lithosphere is generally conductive (<20 Ω·m) with a noticeable east-west orientation. The resistivity model reveals segmented structures along and perpendicular to the rifts, on a scale not seen in previous studies (Jin et al., 2022; Wei et al., 2001), and provides compelling evidence that the extensional history of the region evolved through successive and distinct phases.

The low-resistivity features converge below Qiangtang into a large interconnected structure with multiple channels (Figs. 2C–2G). Deep conductors have been interpreted as partial melts, aqueous fluids, graphite, and metallic minerals (Di et al., 2023; Jin et al., 2022; Comeau et al., 2022). Graphite films are proposed to exist in cool and stable continental regions (Yoshino and Noritake, 2011), rather than hot regions of active accretion, and thus are not considered further here. Hydrogen ions can be formed by the dissociation of water in the upper mantle and can reduce the resistivity and solid phase of the rocks, leading to partial melting (Hirschmann et al., 2009). Aqueous fluids in the mid- to lower crust can be provided by a subducting plate or derived from the thickened crust through metamorphic reactions (Wannamaker et al., 2002).

In accordance with the low temperature (<1200 °C; Sun et al., 2012) and close correlation with low-velocity anomalies from S-wave studies (Hou et al., 2023; see also SM4), the low-resistivity features in the lower crust are best explained by the presence of fluids with a high volume fraction (Figs. 3A–3B; SM5). This can be attributed to some combination of fluids and partial melts (Huang et al., 2020), and possibly mantle volatiles (Jin et al., 2022). The portion of partial melt increases with depth, consistent with water content, suggesting that partial melts are a major component of the deep lithospheric conductors.

The low-resistivity features are embedded in the resistive Lhasa and Himalaya terranes and occupy the lower lithosphere below Qiangtang, terminating at the eastern edge of Tibet. Therefore, the results indicate that the lower crust of Qiangtang is a convergence region for melt-rich fluids from the south, with channels connecting to the upper crust below the Lhasa and Qiangtang north-trending rifts. This implies a transition from vertical pathways in the mantle lithosphere to horizontal structures in the crust, controlling the north-trending rifts and normal faults.

DISCUSSION

Based on constraints from geo- and thermochronology, it is inferred that the east-west–oriented extension and north-south–directed rifting across Tibet developed in two major stages from the Miocene to Pliocene (Kapp et al., 2008; Woodruff et al., 2013). The initial extensional tectonics, associated with southward extrusion along the South Tibetan detachment, have been explained by channel flow in the lower crust (Clark and Royden, 2000). The resistivity model, particularly the lower part of the southern low-resistivity structure, suggests that this channel flow could have been induced by fluids upwelling along vertical pathways in the lower lithosphere rather than by horizontal flow, because of the weak lateral connectivity of the massive structure below the crust. The upward migration of mantle materials is interpreted to have caused weakening of the lower crust of southern Tibet and could have been the trigger for inception of east-west ductile extension. This hypothesis is supported by geophysical and petrological observations that show age and compositional properties (Styron et al., 2015; Lee and Whitehouse, 2007; Williams et al., 2001; Shi et al., 2020). The fluids responsible for these processes may have originated from the subduction of Tethyan Ocean lithosphere, subduction (including tearing and break-off) of the Indian plate, or lithospheric delamination (e.g., Jin et al., 2022; Shi et al., 2020). This interpretation is supported by widespread but variable conductors (30–70 km depths) laterally intruding a resistive lithosphere below Lhasa and connecting with vertical channels, as seen in the resistivity model. Hence, we infer a positive feedback mechanism between fluid migration and extensional deformation, which is accommodated by normal faulting in the upper crust (Figs. 4A–4B).

Decompression melting caused by ongoing extensional tectonics (Brown and Dallmeyer, 1996) led to upwelling below Tibet in the first stage, with fluid flow represented as vertical migration, and enhanced the rifting (Aoya et al., 2005). This hypothesis is supported by petrological and geochemical results from Miocene magmatism (Lee et al., 2011; Ratschbacher et al., 2011). In the second rifting stage of this region, obstructed by the overlying resistive and strong crust (Hou et al., 2023; Jin et al., 2022), the fluid flow likely transitioned to lateral motion after upwelling, affecting inherited rifting, due to the connection of fractures both parallel and perpendicular to the rift axis (Figs. 4B–4C). This is supported by the distribution of Miocene magmatism and volcanism (e.g., Aoya et al., 2005; Lee et al., 2011; Sholeh and Wang, 2021). Seismic anisotropy shows that the upper lithosphere below Tibet is characterized by strong horizontal anisotropy, whereas the lower lithosphere shows a disordered and weak anisotropy (Zhang et al., 2023).

In fact, the stresses associated with vertical mantle convection and fluid flow along a crustal channel can be large enough to enhance continental rifting (Murphy et al., 2019). Geochemical investigations have shown early top-to-the-south thrust-related deformation in southern Tibet after the India-Asia collision (Aoya et al., 2005) and later top-to-the-north extension-

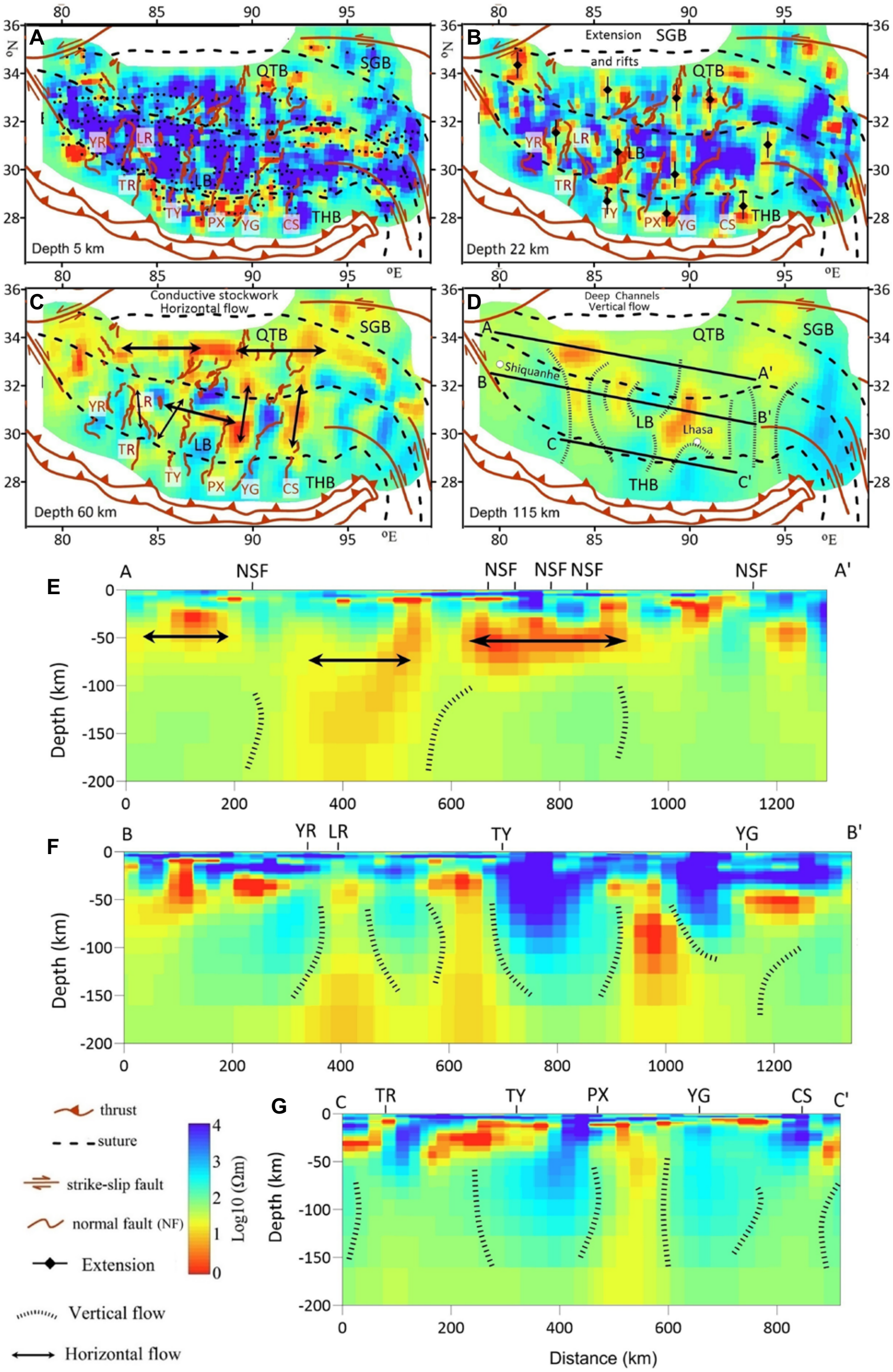

Figure 2. Resistivity model as (A–D) horizontal slices and (E–G) vertical sections. Vertical sections are shown as black lines in D. Locations of rifts/normal faults are marked as red lines or as NSF. Other labels are same as in Figure 1.

related deformation in central to northern Tibet (Lee and Whitehouse, 2007; Aoya et al., 2005). Microstructural analysis and isotopic dating of granites indicate that the extensional deformation began after fluid upwelling (granitic magma intrusion), meaning that extension was not the initial cause of melting (Aoya et al., 2005).

The resistivity model shows that the deep conductors are not directly correlated with surface rifts; rather, they correspond to the typical depth of magma generation. We infer that fluid migration from water-promoted melting has controlled both the earlier thrust-related deformation and later rifting and faulting from south to north, in response to southward and northward material motion (Aoya et al., 2005). Moreover, the existence of both southward and northward fluid flow can be inferred from the contact relationship between the conductive and resistive features, consistent with microstructural observations and granite dating source analysis (Lee et al., 2011; Aoya et al., 2005).

Although rifting is widespread across Tibet, it is more developed in the south, conforming with the distribution of low-resistivity features in the lithosphere. Differences in the electrical signatures of north-trending rifts between southern and northern Tibet can provide useful constraints to identify the mechanism of extension evolution. The low-resistivity features that are widely distributed below Qiangtang in the resistivity model indicate subsequent northward fluid flow and accumulation, consistent with results from (U-Th)/He thermochronology (Styron et al., 2015; Bian et al., 2020) that show younger rifting to the north. Furthermore, the direction of fluid flow may have converted to along-axis flow, i.e., along the middle BNS and eastern JSJS. Thus, the fluids may have spread east-west and accumulated in the lower crust below Qiangtang. Therefore, our model predicts that extension and rifting mechanisms differ between southern and northern Tibet, corresponding to the fluid migration patterns. Moreover, the northern front of the rifting migrated northward, with the location related to that of the northward-migrating mantle fluids, as well as the northern front of the developing extension.

We note that the observed normal faulting in southern and northern Tibet (Bian et al., 2020) is consistent with the pattern of subsidence and crustal thinning predicted by the conductivity distribution. The fluid upwelling hypothesized here can cause extension and rifting, and the proposed horizontal fluid flow explains the weaker extension in northern Tibet. The presence and high rates of northward-directed fluid flow, which has a reduced viscosity ($\sim 10^{18}$ Pa·s; SM5), may reduce or eliminate the energy available for upper-crustal extension in northern Tibet through stress absorption. Then, the fluid accumulation in the lower crust of Qiangtang may provide the conditions for decompression that weakens the deformation upward. This hypothesis is consistent with the rift morphology and thermochronometric results from the major rifts in southern Tibet (Lee et al., 2011) compared to the much smaller, scattered rifts to the north (Yin et al., 1999).

We propose that normal faulting and rifting in the region result from the deformation of the Tibetan crust in response to fluid flow, possibly caused by mantle convective removal and vertical material migration through the mantle lithosphere. Moreover, the crustal deformation is weaker in the north compared to the south (e.g., Spicer et al., 2021), possibly caused by the northward fluid flow and accumulation. In addition, our interpretation can explain why the extensions of the rifts appear to connect with each other in the lower lithosphere and why rift-bounding faults occur on both sides of the Lhasa terrane.

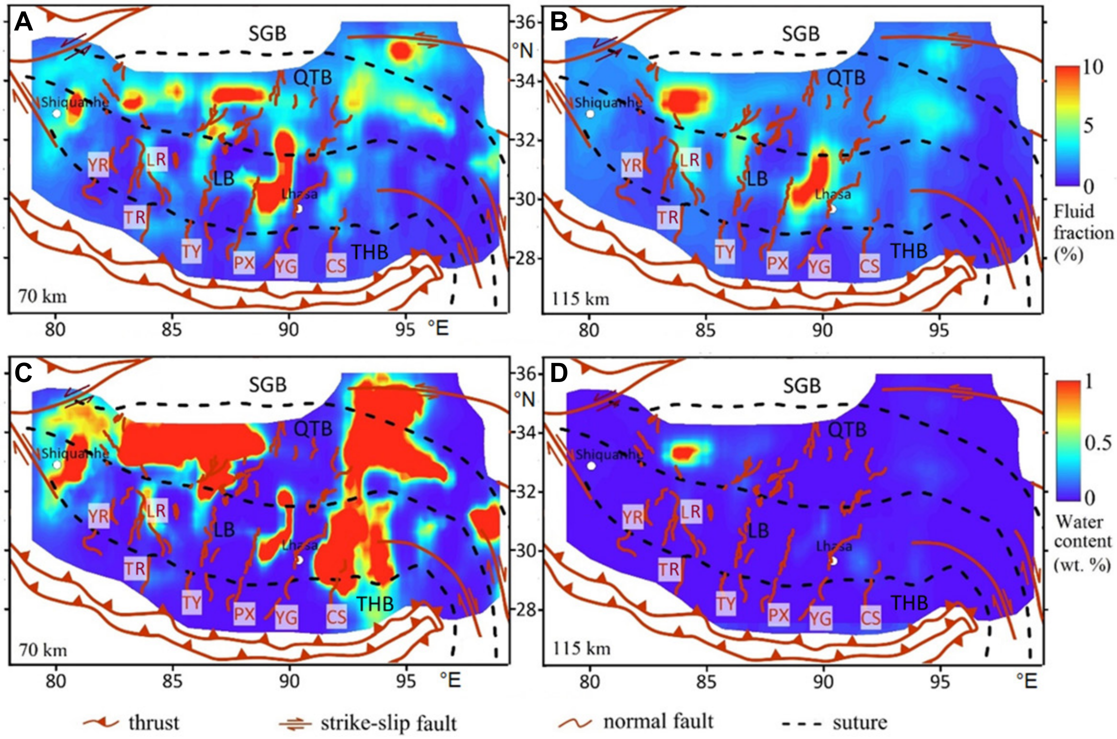

Figure 3. (A–B) Estimation of fluid fraction and (C–D) water content at depths of 70 and 115 km. Rifts/normal faults are marked in red. Other labels are same as in Figure 1.

CONCLUSIONS

To address the unclear mechanisms of extension and rifting across the entire Tibetan Plateau, this study considered the evolution of rifting after the India-Asia collision and worked to integrate existing hypotheses for tectonic adjustments and stress reduction associated with the effects of fluid flow on the surrounding lithosphere. The results show that electrical structural differences preceded rift development related to fluid flow and fluid accumulation. The variable material properties and structure, as evidence by conductive, interconnected, massive structures in the lower lithosphere, resulted in bands of rifts and their distinct development that generated the observed stronger normal faulting in southern Tibet. Our electrical observations, which suggest fluid flow along the rift axis, show that extension is no longer uniformly distributed, but instead is spatially variable, and this variability is dependent on the conditions controlled by multiphase fluid migration. Based on these findings, we propose a multistage growth model for the evolution of rifting and emphasize the critical role of fluid flow in shaping extensional deformation.

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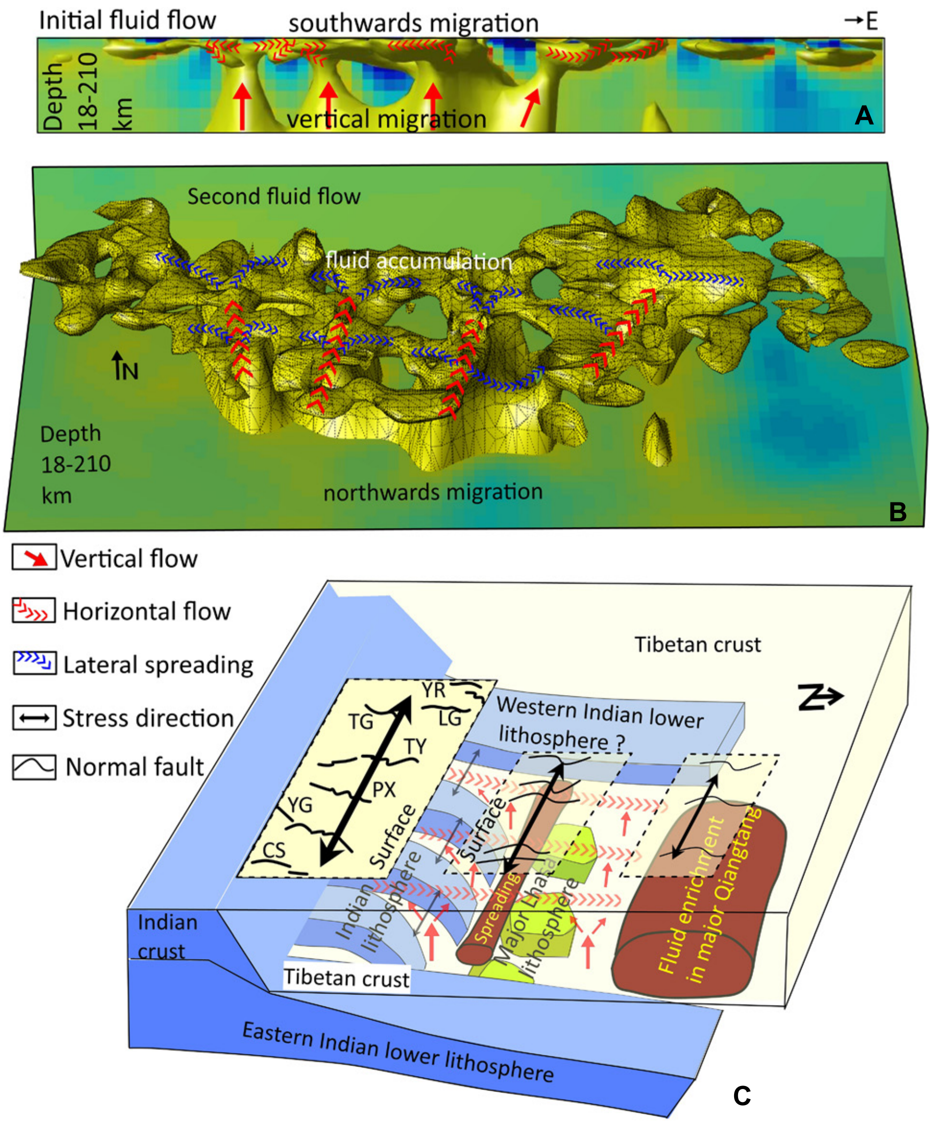

Figure 4. (A–B) Resistivity model with isosurface <40 Ω·m and (C) cartoon of fluid migration model. Below southern Tibet, fluids migrated upward, accumulated in lithosphere, and induced lithospheric rifting by southward flow. Subsequently, fluids migrated northward, accumulated in lower crust of Qiangtang, and induced weaker normal faulting than that in southern Tibet. Labels are the same as in Figure 1.

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